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Investigation of prototype thermoelectric domestic-ventilator

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ABSTRACT

Applications of thermoelectrics had been enlarged from conventional single refrigeration or generation to waste heat recovery with tough energy consumption of the world. With improvement of living standard more and more domestic air-conditioners are used in Chinese families now. Percentage of power consumption of domestic air-conditioner caused by heat load of fresh air supply increased after SARS, which could be prevented efficiently with sufficient fresh air supply, broke out in China in 2003. A novel prototype thermoelectric domestic-ventilator with heat recovery of exhaust of air-conditioned room had been made in Hunan University thermoelectric lab. A thermoelectric heat exchanger and a flat-fin cross flow heat exchanger were integrated in this ventilator. This ventilator was investigated and its cooling (and heating) performance were evaluated in terms of the coefficient of performance, cooling and heating powers, and being handled temperature difference of fresh air. The coefficient of performance of this ventilator was found to be over 2.5 in the whole experiment. The optimal working parameters of this ventilator were studied in this paper. The potential improvements in performances and market prospects were also discussed in this work.

1. Introduction

The technology of thermoelectricity began during the World War Two when Soviet Union, under the Academician Ioffe's inspiration, produced 2–4 watt thermoelectric generators to be capable of powering a small radio from a small cooking fire [1]. Thermoelectric generation had been employed for NASA missions on the moon and the Mars, also found in the nuclear-powered thermoelectric cardiac pacemaker battery [2,3]. Thermoelectric refrigeration had been employed in various cooling applications of small-volume devices, typical of which were to stabilize the temperature of solid-state lasers, to cool infrared detectors and charge-coupled devices, and to increase the operating speed of integrated circuits [4–6]. During recent decades, due to major factors: increasing awareness of the deleterious effect of global warming on the planet's environment, a renewed requirement for long-life electrical power sources, substantial progress had been made in employing thermoelectrics as an environmentally friendly method of recovering industrial waste heat [7–10] and automobile waste heat of engines and exhaust [11–13].

Following development of China's economy, its energy consumption had been very intensive. For example, domestic air-conditioners had been widely used in Chinese families. Power consumption of domestic air-conditioners had been a big part burden for China's power supply. Further more, power consumption of air-conditioner caused by heat load of fresh air supply couldn't be neglected. Especially, it was proved that sufficient fresh air supply could be an efficient way to prevent SARS outbreak.

Fresh air supply of air-conditioned room in China had been solved by simply opening window or ventilating through ventilators with passive heat recovery. The first way resulted heat loss of air-conditioned room. The latter way was high energy efficiency. However, thermal comfort of being handled fresh air was hardly close to indoor ambient in this way for its passive heat recovery limited by thermal parameters of fresh air and exhaust.

Thermoelectric application in this field could be competitive for its novel character. When a direct power supply was connected with the thermoelectric modules, a hot side and a cold side could be set simultaneously. As being a cooler, the hot side was negative effect. In application of thermoelectric ventilator, cold exhaust could weaken its negative effect in summer and cooling performance could be enhanced at the same time. In winter, as being a heater, the cold side could be used to recover heat of exhaust. Under thermoelectric ventilator's active heat recovery, fresh air could be handled close to indoor air thermal parameter in high energy efficiency.

So a novel concept of domestic thermoelectric ventilator had been studied and tested. In this study, a prototype thermoelectric ventilator had been constructed based on commercially available ventilators. The objectives of this study were intended to provide an evaluation of energy efficiency and market prospects of thermoelectric ventilator and to identify areas for further improvement.

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Nomenclature

Q_c	cooling rate of thermoelectric module (W)	P_f	power consumption of fans (W)
Q_h	heating rate of thermoelectric module (W)	P_t	power consumption of thermoelectric modules (W)
α_{ab}	seebeck coefficient for a module	G_1	fresh air volume (m^3/h)
T_c	cold side temperature of thermoelectric module (K)	i_1	enthalpy of fresh air before being handled (KJ/KG)
T_h	hot side temperature of thermoelectric module (K)	i_2	enthalpy of fresh air after being handled (KJ/KG)
I	electrical current (A)	ΔT	temperature difference (K)
R	electrical resistance (Ω)	COP	coefficient of performance
K	thermal conductance (W/K)		

2. Prototype

This thermoelectric ventilator was composed of two centrifugal fans, a flat-fin cross flow sensible heat exchanger made of aluminium, air duct, a thermoelectric modules heat exchanger made by thermoelectric modules and flat-fin heat sinks made of aluminium. The overall dimension of heat sink was $120 \times 120 \times 13$ mm with 18 fins. The dimensions of the fins were $120 \times 12 \times 1$ mm. The overall dimension of the flat-fin cross flow sensible heat exchanger was $120 \times 120 \times (13 \times 8)$ mm. The overall dimension of the thermoelectric modules heat exchanger was $120 \times 120 \times (13 \times 8 + 3.8 \times 3)$ mm. Different from market available ventilators with passive heat recovery, this ventilator was integrated with a flat-fin cross flow sensible heat exchanger and a thermoelectric modules heat exchanger to enhance heat recovery from exhaust. As a domestic application, this ventilator should be compact enough to match Chinese's small apartment. So, how to optimize this ventilator's structure and meet the basic requirement of ventilation had been paid more attention. This ventilator's overall dimension was $400 \times 310 \times 260$ mm.

As shown in Fig. 1, a cross flow sensible heat exchanger and a thermoelectric modules heat exchanger had been made in cubical shape separately. They were placed as shown in Fig. 1. Air tunnel of intake and outlet were connected by air ducts. With this placement, condensed water from air could be collected and the ventilator's pressure loss could be lessened. The thermoelectric modules heat exchanger's performance was determined by its construction directly. Reducing of contact resistance and cold bridge were focused. Thermal conduct grease was filled in the contact surface of modules and sinks. Screw bolts with thermal insulating casing were used to connect heat sinks and modules as a whole. Thermal insulating material was filled on the surface of the thermoelectric heat exchanger. Thermal insulation was Armaflex with 5 mm thick and a conductivity of 0.03 w/m.k.

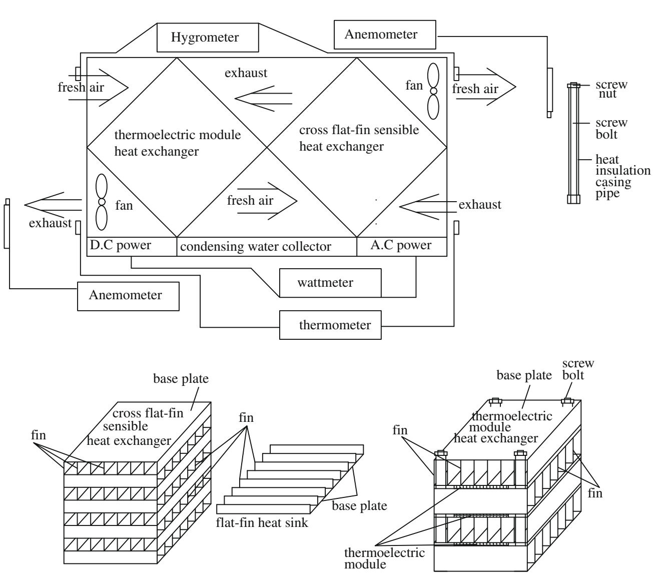

Fig. 1. Schematic of thermoelectric domestic-ventilator.

As a ventilator, ventilating volume was an important work parameter. Being a household application, three people's family was considered here. According to basic healthy specification that everyone needs 20 m^3/h in an air-conditioned room, air volume of this ventilator ranges from 70 to 60 m^3/h.

Compact profile dimension of the ventilator meant pressure of fans could be wasted to overcome system resistance. Fans could hardly reach theirs standard gauge values. Two centrifugal fans with high pressure were chosen here, with standard gauge values: 120 m^3/h, 140 Pa, 58 W, 0.16 A, 2000 r/min, 50 db.

Thermoelectric modules used in this study were manufactured by Hualeng, China [14]. Size of thermoelectric modules was $40 \times 40 \times 3.8$ mm, with 127 thermoelectric couples of bismuth telluride and ceramic surface, type of TEC12706. There were 10 TEC12706 modules used here. Every two modules were in serial as a team and five teams were in parallel as a whole.

D.C power supply's voltage ranged from 0 to 24 V, with maximum power output 240 W, size of $199 \times 110 \times 50$ mm. Its ripple coefficient of voltage was less than 1%.

3. Experimental methodology

Two hot ball anemometers (range: 0–10 m/s, accuracy 0.05 m/s) were used to measure the air velocity, which were located in the outlet of fresh air and exhaust, respectively. From collected data, it can be found that air volumes of fresh air and exhaust were the same for the symmetry of both air tunnels placement. Both fans was connected with an adjustor of velocity, which was used to change the air volume from 70 to 60 m^3/h.

Two thermocouples thermometer of type TM-902C(range: −50 to 130 °C, accuracy ±1 °C), located in outlet and inlet of exhaust, were used to measure its changes of temperature.

Two hygrometers of type TES-1360(range: −20 to 60 °C, 10–95%, accuracy ±0.8 °C, ±3%), located in outlet and inlet of fresh air, were used to measure its changes of temperature and relative humidity.

A wattmeter of type JB2170-77(range: 0–1500 watt, accuracy ±5 watt) was used to measure power consumption of thermoelectric modules and centrifugal fans.

The experiment of this study included the winter part and the summer part. The instrumentation's distribution of sensors for temperature, relative humidity, air velocity, and power output was shown in Fig. 1. In each part of the test, in order to find optimal air volume and voltage of the thermoelectric modules, ventilator's performances were compared, respectively. The air volumes were set in turn from 70(hi), 65(me), to 60(lo) m^3/hour and fans' power consumption were from 60, 45, to 30 watt. The voltages of the

thermoelectric modules were set in turn from 8, 10, to 12 volt and its power consumption were from 75, 110, to 150 watt.

Thermoelectric modules' performances could be determined by the scale of voltages applied on the thermoelectric modules, for the current driven through the modules could be an important factor in thermoelectric performance, as shown in the equations of (1) and (2). Based on the working parameters of TEC12706 [14], single module could be gained the maximum cooling power 51.4 watt under the voltage of 15.4 volt and the current of 6 ampere. Its electric resistance ranged from 1.7 to 2 ohm. According the reference [15], the half value of the current under the maximum cooling performance could be a optimum value for thermoelectric performing. So the voltages applied on every single module were set in turn from 4, 5, to 6 volt, and the D.C power supply output voltages were set in turn from 8, 10, to 12 volt, respectively.

In winter, the ventilator was tested under real working condition which indoor space was heating by a domestic air-conditioner. As the heat-pump air-conditioner with electric heating, the temperature of indoor ambient would fluctuate for its suddenly defrosting and electric heating. So indoor temperature fluctuated in a range (15–23 °C). The outdoor temperature could be relative stable (6–8 °C) without much fluctuation.

In summer, the ventilator was tested under simulated working condition which indoor thermal environment parameters were set similar to summer indoor air-conditioned situation (about 22–24 °C) by natural condition and outdoor hot environment (35–40 °C) simulated by a heater. So relative humidity value of outdoor in this situation was less than real working conditions.

4. Result analysis

Thermoelectric cooling and heating performance could be expressed by following equations:

$$Q_c = \alpha_{ab} T_c I - \frac{1}{2} I^2 R - K(T_h - T_c), \quad (1)$$

$$Q_h = \alpha_{ab} T_h I + \frac{1}{2} I^2 R - K(T_h - T_c), \quad (2)$$

where the prototype thermoelectric module's physical parameters, included α, K, R, could be taken as constant. Thermoelectric cooling and heating performances were mainly determined by T_c, T_h and I. Better performance could be achieved by enhancing the heat transfer and a reasonable construction.

The heating or cooling power of the prototype could be expressed by

$$Q = G_1(i_2 - i_1)\rho, \quad (3)$$

where ρ was the density of fresh air. The COP of the prototype could be expressed by

$$\mathrm{COP} = Q/(P_f + P_t). \quad (4)$$

As shown in Fig. 2, three periods of time's axis were defined as air volume changing in turn from "hi", "me", to "lo". Here 0 v meant fresh air was handled by passive heat recovery. Under the same voltage ventilator's heating power rose with the increase of air volume. Under the same air volume, heating power rose with voltage increasing.

Handled temperature difference (TD) of fresh air could be used to judge its thermal discomfort, which was caused by big difference of thermal situation of the air-conditioned room and the outdoor. Bigger TD meant fresh air had been handled closer to indoor air situation. Curves in Fig. 3 showed, under the same air volume, value of TD rose with voltage increasing. Based on the figures above, it could be found that the ventilator heating performed better under 12 v condition.

The ventilator's coefficient of performance (COP) was calculated to seek its optimum working parameters. As shown in Fig. 4, the ventilator's COP could be over 2.3. Under the same air volume, value of COP rose with the reduction of voltage.

As mentioned above, maximum heating power was gained under 12 v condition. While the maximum COP was gained under 8 v condition. In order to find the balance point between heating power and energy efficiency, condition under 10 v could be a good choice.

In general, air volume of "hi" and voltage of 10 v could be the optimum working parameters in winter.

Handled temperature difference of exhaust (ETD) was measured to find relation between heating performance and heat recovery. As shown in Fig. 5, under the same air volume, value of ETD rose with heating power increasing except condition under 12 v. This could be due to constant surface area of the ventilator's heat exchanger, so that heat of cold side of thermoelectric modules couldn't be transferred to the exhaust timely. Some big fluctuating points of ETD could be collected in the period of defrosting of indoor air-conditioner. So hot exhaust blended with cold return air from air-conditioner could lead the temperature of exhaust around outlet to decline and ETD to fluctuate further.

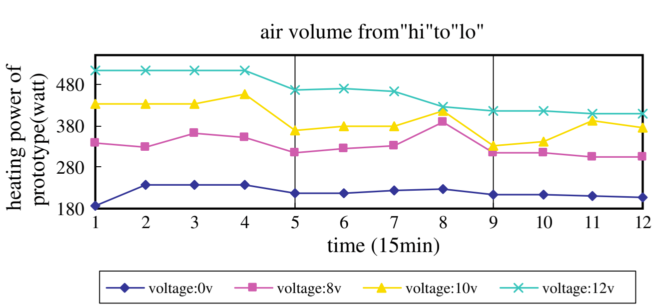

Fig. 2. Heating power of ventilator under the different voltages in winter.

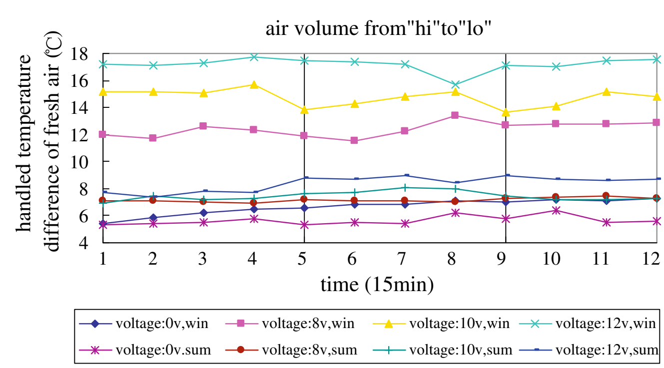

Fig. 3. Handled temperature difference of fresh air under the different voltages.

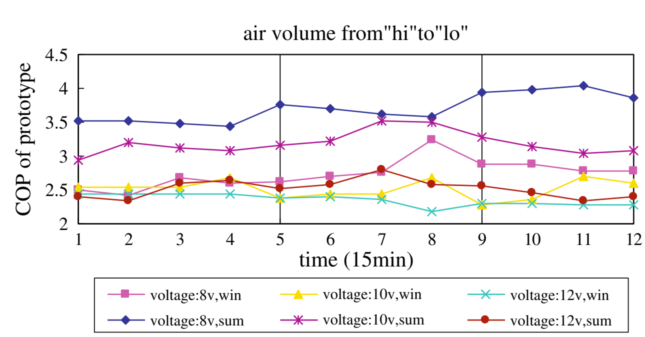

Fig. 4. Coefficient of performance of ventilator under the different voltages.

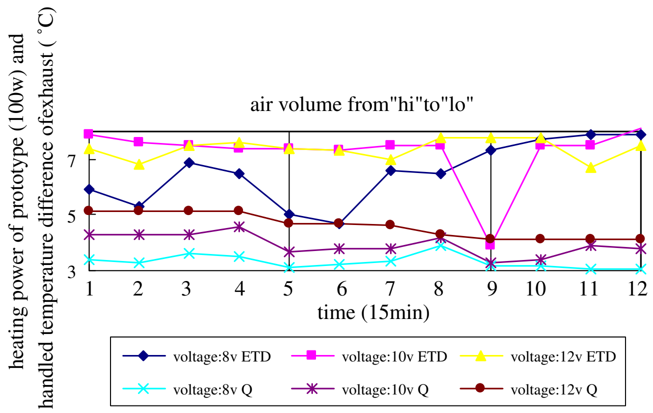

Fig. 5. The comparison of heating power and temperature difference of handled exhaust in winter.

As shown in Fig. 6, the ventilator gained the minimum cooling power without thermoelectric cooling. Under the same air volume its cooling power rose with voltage increasing. Curves of 10 and 12 v were adjacent. This could be due to limitation caused by constant area of heat transfer and increasing heat flux with higher voltage applied.

Handled temperature difference (TD) of fresh air could be used to judge the ventilator's cooling performance here. As shown in Fig. 3, under the same air volume, its TD rose with voltage increasing.

Relative humidity as a main parameter for thermal comfort was measured here. As shown in Fig. 7, dehumidifying of fresh air happened under the all condition. The maximum difference of relative humidity could be gained under the condition of 10 v.

As the COP curves shown in Fig. 4, this ventilator could be run under COP value over 2.5. Under the same air volume, its COP rose with voltage decreasing. Increasing of voltage applied on thermoelectric modules meant more power was input to cause the higher heat flux, which was hardly to be transferred timely through common heat transfer. Under the same voltage the ventilator could be gained its maximum COP value at the "me" except under 8 v.

So it could be found that condition under "me" and 10 v was optimum working parameter in summer.

Temperature difference of exhaust (ETD) from original state to being handled was measured like in the winter part. The relation of ETD and COP was obvious, as shown in Fig. 8. Under the same voltage, curves of COP and ETD had same trend.

In general, under the same air volume, ETD rose with COP declining. This might be explained that its capability of heat recovery could be partly determined by its energy efficiency in summer working situation. More attention should be focused on the improvement of heat transfer of ventilator's thermoelectric exchanger.

5. Discussion

Fresh air supply of air-conditioned room of Chinese families could be solved by opening window or ventilating through ventilators with passive heat recovery such as sensible heat recovery or total heat recovery.

From the test results, we could compare the thermoelectric ventilator with above two ways from aspects of COP, thermal comfort and cost.

5.1. COP

As shown in Fig. 4, the thermoelectric ventilator could be run under a COP value of over 2.5. Average COP of most domestic air-conditioners used in China was around 2.5 [16]. So, the thermoelectric ventilator could be used to handle heat load of fresh air as efficient as domestic air-conditioners.

Without the use of CFCs in conventional domestic air-conditioner, the thermoelectric ventilator could be an environmental friendly replacement for compressor-type air-conditioners in fresh air supply. Even hot island effect of Chinese cities in summer, partly caused by air-conditioner's condensed heat, could be improved with thermoelectric ventilator applied.

The heat load of fresh air of ventilators with passive heat recovery, Q_l, could be described as

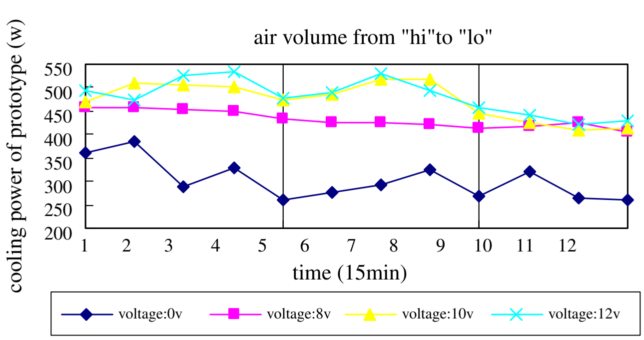

Fig. 6. Cooling power of ventilator under the different voltage in summer.

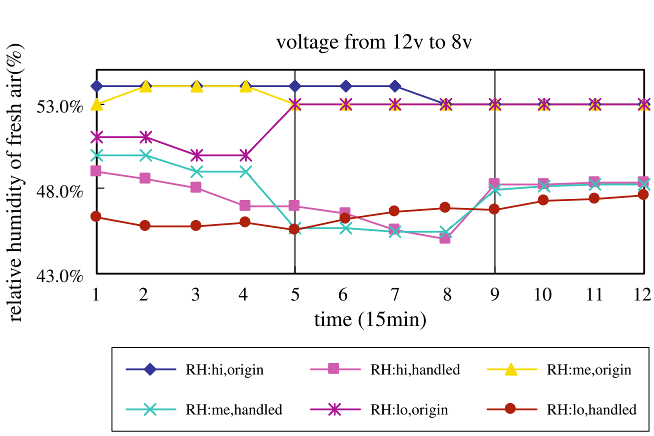

Fig. 7. Relative humidity of fresh air from origin to being handled in summer.

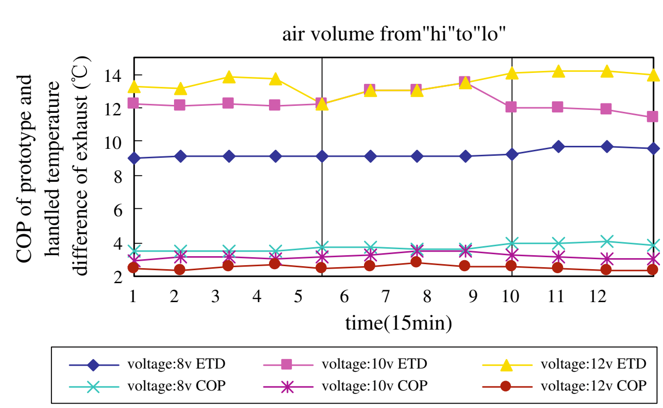

Fig. 8. The comparison of coefficient of performance and handled temperature difference of exhaust in summer.

$$Q_l = P_f \times COP_r \tag{5}$$

The heat load of fresh air of the thermoelectric ventilator could be described as

$$Q_{lv} = (P_f + P_t) \times COP_{tr} \tag{6}$$

Apparently, if $Q_l = Q_{lv}$, under same fresh air volume, COP_{tr} couldn't compete with COP_r for additional power consumption P_t. If only compared from COP, the thermoelectric ventilator couldn't be a powerful competitor to ventilators with passive heat recovery. However, as an active heating and cooling device thermoelectric ventilator could break some limits of passive heat recovery and improve the thermal comfort of fresh air.

5.2. Thermal comfort

When opening window for ventilation, fresh air blended with indoor air directly could lead to less thermal comfort for occupants. Under being handled by thermoelectric ventilator, as shown in Figs. 2, 3 and 6, fresh air could be handled close to indoor air thermal parameters before being blended with indoor air. At the same time, as a kind of organized ventilation, fresh air supply can be more sufficient and efficient through thermoelectric ventilator application.

Ventilators with passive heat recovery, which were limited by temperature difference between exhaust and fresh air, couldn't achieve better performance than thermoelectric ventilator. In this test, under 0 voltage situation, this thermoelectric ventilator could be used as a ventilator with passive heat recovery through a cross flow heat exchanger. As shown in Figs. 2, 3 and 6, comparing handled temperature difference(TD) of fresh air, heating power and cooling power of ventilator, under 0 v and thermoelectric effect working, thermoelectric ventilator could be a powerful competitor. The TD with passive heat recovery was less than the TD with the thermoelectric active heat recovery 5–10 °C in winter and 2–3.5 °C in summer. Obviously in latter way fresh air could be handled close to indoor air thermal parameters. As shown in Fig. 7, thermoelectric ventilator could be used to dehumidify the fresh air actively in summer.

In general, thermoelectric ventilator could be run in high energy efficient way and achieve the best thermal comfort and necessary sanitary ventilation, which were hardly to achieve for the above other ways of fresh air supply.

5.3. Cost

Period (year) of thermoelectric ventilator cost returning could be expressed as

$$T = \frac{C_v}{Q_{re} \times T_1/1000\ \text{watt} \times 1\ \text{hour} \times P_e} \tag{7}$$

Here C_v was cost of thermoelectric ventilator, Q_{re} was heat recovery from exhaust of air-conditioned room and T_1 (hour) was running time of ventilator per year, and P_e was price of domestic electricity. It could be found, from Eq. (7), that T could be shorten by decreasing C_v and increasing Q_{re}, T_1, P_e.

C_v consisted of costs of ventilator's frame structure and envelope, the flat-fin exchangers, fans, the D.C power supply, the thermoelectric modules. Most of cost could be focused on the last three.

Cost of fans was about 20% of the whole. As a common fluid machine, fans' cost could only be cut from price difference between retail and whole sale.

Cost of D.C power source was about 30% of the whole and could be cut not only from price difference between retail and whole sale, but also through mass production with electronic industry development.

Thermoelectric modules' cost was about 35%. Its cost could be saved from more efficient thermoelectric material applied, which meant to achieve same performance and less thermoelectric modules needed. More and more new thermoelectric materials had been studied. The research of thermoelectric material's structure in nano scale had been made more progress [17–19].

Increase of Q_{re} could be achieved through more efficient heat exchangers application.

T_1, as running time of ventilator in air-conditioning seasons, could be increased with living standard rising of Chinese families.

P_e of China is lower than most developed countries for Chinese government's huge subsidy in power generation industry. With more and more tough energy supply around the world, Chinese government will decrease its subsidy gradually in order to push energy efficiency improvement in whole society. P_e won't be on low level in the future.

In general, period of thermoelectric ventilator cost returning could be shortened from materials advancing and industrial mass production and energy cost reform in China. So, thermoelectric ventilator could be more competitive in future.

5.4. Thermoelectric ventilator's performance further improvement

In order to enhance heat transfer, heat pipe exchangers and a kind of combination of fin-type exchanger and enclosed natural liquid cycle system will be applied in further study.

More and more marketable heat pipe exchangers for personal computer meant their cost declining and more choices. So heat pipe exchangers could be chosen to weaken high intensive heat flux. Heat transfer between fresh air and exhaust could be more sufficiently and quickly, under the heat pipe exchanger applied.

The enclosed natural liquid cycle system combined with common the fin-type exchanger could facilitate to reduce the heat flux from hot side of thermoelectric modules. The liquid could be driven to circulate through difference of its density. The heat removed by the circulating liquid could be rejected by its radiator. And the air flux could be used to enhance the heat transfer of radiator's forced convection. This system's pipes were fixed in the tunnel of fin-type exchanger and contacted with exchanger's surface to absorb the heat rejection of thermoelectric modules sufficiently. In this way air flux could be used to remove heat rejection from fin-type exchanger and radiator at the same time. For no additional power input, higher capacity of heat recovery and energy efficiency could be expected.

6. Conclusions

A prototype domestic thermoelectric ventilator with heat recovery from exhaust of air-conditioned room was constructed and tested in this study. It could be run with the COP over 2.5 in summer and winter. Compared to the conventional fresh air supply of domestic air-conditioned room such as simply opening window and ventilating through ventilators with passive heat recovery, this prototype thermoelectric ventilator could achieve sufficient and necessary sanity ventilation and the best thermal comfort of fresh air supply with high energy efficiency. Its optimum working parameters were found through the test. Moreover, further improvements in the COP and cooling and heating performance may be possible through improving thermoelectric modules' contact-resistances, thermal interfaces and heat exchangers. Its market prospect can be very broad with cost decrease led by development of high performance thermoelectric materials and more and more marketable high efficient heat exchangers and D.C power supplies.

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